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BLAST ATTENUATION STUDIES IN DIVIDING WALL PROTECTIVE CONSTRUCTION

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U. S. Army Engineer Waterways Experiment Station
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FOREWORD

This paper presents the preliminary results of an investigation authorized by the Armed Services Explosives Safety Board as a part of the supporting studies for the design of facilities to reduce the risk of explosion propagation being conducted by Picatinny Arsenal.

The investigation is being conducted at the Concrete Division of the Waterways Experiment Station under the general supervision of Messrs. Bryant Mather, James M. Polatty, and Ralph A. Bendinelli.

This paper was prepared for presentation at The Eighth Annual Explosives Safety Seminar on High Energy Propellants held at Huntsville, Alabama, on 9-11 August 1966. It was reviewed and approved by the Office, Chief of Engineers.

The authors wish to thank Mr. Stanley Wachtell of Picatinny Arsenal for his assistance and advice during this investigation.

Colonel John R. Oswalt, Jr., CE, was Director of the Waterways Experiment Station during the preparation of this paper. Mr. J. B. Tiffany was Technical Director.

BLAST ATTENUATION STUDIES IN DIVIDING WALL PROTECTIVE CONSTRUCTION

INTRODUCTION

1. The ever-present possibilities for accidental detonations of explosives and high energy propellants in facilities for manufacture, maintenance, and storage of such materials pose a serious problem of reducing the blast effects on adjacent areas. The high shock pressures associated with a large explosion are sufficient to destroy conventional structures and to produce fragments of sufficient energy to cause propagation between adjacent bays of ammunition storage and processing complexes. Previous studies have established that high velocity fragments are a principal mechanism of propagation.

2. The experimental test program being conducted at the Waterways Experiment Station (WES) is designed to compare the effectiveness of various wall protection schemes in reducing the peak pressure transmitted to a final structural wall from an accidental explosion. Possible dissipative materials are selected on the basis of the waste-heat concept. The wall protection schemes are developed using both specially formulated dissipative materials and impedance mismatch configurations in an attempt to reduce the peak pressure transmitted to a final structural wall.

APPROACH

Theoretical

Waste Heat

3. The waste-heat concept embodies the principle that a portion of the energy of a shock wave is irreversibly lost in raising the temperature of the medium through which it propagates. This concept was first proposed by F. B. Porzel[1*] in 1957.

4. Shock wave energy may be partitioned into two main categories of kinetic and internal energy as shown in fig. 1. Energy at the shock front is partitioned equally into internal and kinetic, shown separated by the Rayleigh line connecting the initial and final shocked states. The waste-heat fraction is defined by the area bounded by the Rayleigh line and the Hugoniot of the respective material. This energy is evidenced as a temperature rise in the medium through which the shock wave propagates. Kinetic energy is due to the velocity imparted to the particles which subsequently becomes available through momentum transfer.

5. The hydrodynamic energy is due to compression of the medium and, subsequently, becomes available through expansion and continues to support a shock wave. This fraction may also be reduced using materials which exhibit a hysteresis effect in its loading and unloading stress-strain relationships; however, the strain energy associated with most distended materials should be low. Although it is highly compressible, air is a highly efficient transmitter of shock energy. The process is reversible and the hydrodynamic energy is returned to further support the shock.

* Raised numerals refer to similarly numbered items in the Literature Cited at the end of this report.

Also, both solids and liquids are efficient transmitters of shock energy in the pressure range of a few kilobars.

6. Idealized composites, as studied theoretically by M. A. Chaszeyka[2], indicate that the waste-heat fraction can amount to as much as fifty percent of the total energy contained in the shock wave. This would require a vertical Rankine-Hugoniot (R-H) curve above the locking pressure for a material composed of a mixture containing appreciable amounts of entrained air. While this is not physically easy to accomplish, it can be approximated using materials which exhibit R-H curves such as shown in fig. 1. The R-H curve shown has not been experimentally determined in this pressure range for the materials tested; however, this relationship can be closely deduced through comparison with tests on similar distended materials.

7. A material consisting of a composite of air and solids takes advantage of the high compressibility and temperature rise of air under shock loading. During loading the air fraction will be compressed and the temperature rise quite high, whereas the solid fraction will barely decrease in volume and the temperature rise will be insignificant.

8. The heat transfer process at these elevated temperatures and pressures is very complex. The efficiency of this process is dependent on the temperature differential between the solid surface and the air. Also, the time available for this transition to occur is relatively short, being the same order of magnitude as the rise time of the pressure. It is assumed that, as the solid fraction crushes into the voids, the particles are pulverized and are mixed intimately with the air in such a way that the equilibrium temperature is reached within the period of the rise time of the

shock pressure. Despite the small mass of the air, the high temperature represents substantial energy. The reasons for limiting the air fraction are of a practical nature. If the air fraction is too high, then the composite behavior will approach that of air since the solid mass may not be sufficient to absorb the thermal energy, i.e., would be less efficient as a heat sink. Also, if the air temperature is high enough to cause vaporization of the solids, then the expansion adiabat would be that of a gas.

9. Theoretical studies of blast effects in idealized composite materials and various soils have been conducted by M. A. Chaszeyka and F. B. Porzel[3]. The results of their study indicate that a composite material containing 80 percent air and 20 percent solids by volume has a peak overpressure versus distance curve which decays as $\frac{1}{R^6}$. Composite mixtures containing equal proportions of air and solids show a pressure decay proportional to $\frac{1}{R^7}$. These values, when compared to the spherical divergence associated with air which is proportional to $\frac{1}{R^3}$, represent a substantial effect of entrained air on peak stress attenuation.

Impedance Mismatch

10. The second method of reducing blast pressures is by the use of laminated materials in which the laminae possess widely differing shock impedances. Fig. 2 shows the relationship between stress and particle velocity for three materials, solid concrete, cellular concrete, and foamed plastic. The behavior of a shock wave at an interface can be understood from a graphical representation provided the unloading path from a shocked state is known. It can be shown that the initial peak shock pressure can be substantially reduced through several

mismatch interactions. In this simplified analysis attenuation effects are not included; however, the effect would be to reduce the peak pressure further. Materials which possess the greatest mismatches are obviously the best choices for the laminate construction. The thickness of the laminae cannot be arbitrarily chosen since the reduction in pressure may be lost if reflections occur which "shock-up" the low impedance materials. These should be chosen on the basis of the expected pulse length and the velocity of propagation in the various laminates. The use of mismatch laminates following attenuating materials may prove to be a rational scheme since the shock pressure should drop off rapidly through the attenuating material, and there will be a trade-off point where any additional energy absorption may not be worth the higher reflected stress into the final structure. The higher reflected stress could be lowered through the use of materials with lower shock impedance when compressed. This is shown in fig. 2 using a foamed plastic.

11. Foamed plastics in locked states are believed to exhibit a R-H equation of state comparable to the solid material from which they are foamed. Therefore, the reflected P-U curve shown in fig. 2 is that of lucite. The stress imparted to the final wall is reduced to approximately one-half of that resulting from the use of cellular concrete as the final laminate.

Experimental

12. A series of ests were designed study the effectiveness of various wall protec on schemes in reducin he peak reflected stress imparted to a final wa Various distended materials were tested in a configuration which has a reasonable similarity to small scale slab tests conducted by Picatinny Arsenal[4]. Protective construction of the sand-filled sandwich type has shown some promise in previous studies in the dividing wall program; and is, therefore, used as a basis for comparison with other protection schemes.

13. The test configuration is shown in fig. 3. From practical considerations, the scale factor for these tests was selected to be 1/6. Full scale is taken to be a standard one-ft-thick dividing wall with a storage capacity of 270 lb of high explosive. It might also be noted that this corresponds to a scale factor of 1/2 for comparison with the 1/3 scale slab tests using 10 lb of composition "B" explosive.

14. As shown in fig. 3, the flight of a free surface pellet is photographed at 5000 frames/sec for which the velocity is computed. The aluminum acceptor plate is fitted with O-rings to prevent blow-by of the burning gasses which would obscure the flight of the pellet.

15. The method of Rhinehart[6] is used to provide a method of measurement of the peak stress produced by explosive loading. This method involves the measurement of the velocity imparted to a small pellet when placed on the free surface of an aluminum plate. Aluminum was chosen because its acoustic impedance is approximately that of concrete. The peak stress is related to the free surface velocity (V) of the pellet

as follows:

$$\sigma = \rho_o \, C \, V/2$$

where:

ρ is the density, and

C is the acoustic velocity of the aluminum plate.

The absolute accuracy of this technique is contingent on a number of assumptions.

a. It is assumed that the incident compression pulse is of the shock type, i.e., that it has a very steep rising shock front.

b. It is assumed that the pressure profile of the rarefaction is identical to that of the incident compression at the instant it reaches the free surface.

Materials

16. Previous investigation at WES of shock-absorbing materials in connection with hardened structures has produced cellular concretes with the following properties:

a. Density 20-40 lb/cu ft;

b. Air fraction 30-60 percent;

c. Static yield stress 50-500 psi.

The voids are evenly dispersed within a brittle matrix of hardened cement paste through the use of foaming agents. The density of these mixtures may be increased using higher density fillers. Expanded portland-cement grout has been proportioned with a density of 135 lb/cu ft and approximately 40 percent voids, however, the elastic yield stress is significantly higher. The physical properties for the materials tested

to date are shown in table 2. It seems desirable, also, in order for a material to be truly dissipative it must also have high thermal conductivity. In order for the solid phase to subdivide or shatter under shock-loading and mix with the air phase, the voids should be small and evenly dispersed within a low strength brittle matrix. The indications are that this feature should facilitate the transfer of thermal energy.

17. An additional series of tests is planned for the following varieties of foamed sulfur samples as furnished by Southwest Research Institute.

a. Specimen No. 1: 23.9 lb/cu ft rigid sulfur foam.

b. Specimen No. 2: 21.9 lb/cu ft rigid sulfur foam.

c. Specimen No. 3: 15.1 lb/cu ft rigid sulfur foam.

d. Specimen No. 4: 14.2 lb/cu ft rigid sulfur foam.

e. Specimen No. 10: 38 lb/cu ft sulfur-vermiculite concrete.

f. Specimen No. 10: 38 lb/cu ft sulfur-vermiculite concrete.

g. Specimen No. 11: 48 lb/cu ft sulfur-vermiculite concrete.

h. Specimen No. 11: 48 lb/cu ft sulfur-vermiculite concrete.

Future tests will also include some polyurethane samples. These materials will be tested to determine both the dissipative characteristics and usefulness as low impedance materials to be used in laminate mismatch studies.

Results and Discussion

18. Several tests were repeated to check the reproducibility of the stress measurement. Due to the spherical geometry of the shock

front and the propagation path through dissimilar materials, a direct peak stress measurement is questionable. However, for a relative indication of the peak stress in the present configuration, the free-surface-pellet technique appears to be valid to within ± 5 percent. The results of tests conducted to date are shown in table 1. The first four tests were conducted for check-out purposes on camera timing, alignment, and method of pellet placement.

19. The velocity pellets were held in place with a thin oil film between hand-lapped surfaces. Both surfaces of the pellet and plate were lapped before each shot. Bond of this type provided an interface essentially transparent to the incident compressive pulse and opaque to the reflected rarefaction pulse. The bond strength, being only a few psi, should have a negligible effect on the free surface velocity since separation will occur for a very low, net, tensile stress.

20. Rounds No. 5 and 6 were conducted to establish the peak reflected stress from an unprotected wall at a Z distance of 0.5. The peak stress of 31,300 psi correlates closely with theoretical predictions[5]. Rounds 7 and 8 established the peak stress at a Z distance of 0.8 to be approximately one-half that measured at a Z distance of 0.5. This is expected since the air-shock pressure is diminished through geometric dispersion by close to the same amount. A total thickness of 6 in. of aluminum was used in Round No. 9 consisting of three 2-in. plates. The Z distance measured to the near surface of the donor plate was 0.5, while the final acceptor plate was at a Z distance of 0.8 for a comparison with Rounds 7 and 8. This shot shows that the stress reduction

through four inches of aluminum is comparable to the same thickness of air, with only geometric dispersion being significant. The results of 7, 8, and 9 show the reproducibility of the tests to be within the accuracy expected.

21. A model of the sand-filled sandwich protection scheme was tested in Rounds 10, 11, and 12. The transmitted stress was not reduced through the use of 2 in. of sand. The particle size of the sand was centered around a sieve size No. 50, similar to the sieve analysis for previous studies conducted by Picatinny Arsenal.

22. Rounds 7-12 give a standard of comparison for all attenuating materials and configurations to be tested which is approximately 47.5 ft/sec at 14,550 psi.

23. Rounds 13 and 15 were of the sandwich type using 2 in. of cellular concrete Mix No. 1, as listed in table No. 2. These results indicate a stress reduction of approximately 25 percent.

24. Cellular concrete Mix No. 2 was tested in Round No. 16. The test configuration was again of the sandwich type. Although only one test has been completed on this material, the stress measurement was slightly lower than Rounds 13 and 15, indicating approximately 35 percent stress reduction in addition to the geometric dispersion as measured in the standard tests.

25. Rounds 17, 18, and 19 were tests on cellular concrete and expanded concrete; however, the test configuration consisted of 4 in. of the test material and a 2-in. acceptor plate. Rounds 17 and 18 were at a Z distance of 0.5 to the near surface of the concrete (for comparison with Rounds 7-13) and consisted of Mixes No. 3 and 1, respectively.

Round 19 was cellular concrete Mix No. 4 at a Z distance of 0.5 to the near surface of the aluminum plate for comparison with Rounds 5-6. Round 17, highest density mix tested, showed nearly a 20 percent reduction of stress. Round 18, having the lowest density, indicated no reduction, while Round 19, with material having a density three times higher and void ratio of one-half as much as Round 18, produced nearly 20 percent reduction.

Conclusions

26. From the limited number of tests conducted to date, the conclusions which can be deduced with reasonable certainty are limited. The first phase of this study was conducted in an exploratory manner, and the data thus generated should be regarded as such.

27. The method of test appears to be adequate for a comparison of dissipative materials and various protection schemes. Pellet velocities and computed pressures correlate closely with those predicted from theoretical computations of reflected pressures.

28. The tests of the sand-filled sandwich-type configuration, using sand as a filler material, has shown no reduction in peak stress. All cellular concrete mixtures proportioned for this study have indicated a reduction of 20-35 percent in peak stress transmitted to the acceptor plate. Mixture No. 1 being the lowest density, lowest yield strength, and highest void fraction has been less effective as a dissipative material. Mixture No. 2, which has a higher density and a significantly higher yield-stress, has shown greater stress reduction despite

the smaller void fraction. Additional tests are needed on these materials; however, the implications are that a higher density with similar compressive strength and void ratio as Mixture No. 1 is desirable. Exposing these materials to a higher stress level did not yield greater stress reduction as shown in Rounds 17 through 19. Round No. 18 indicates an even higher reflected stress than when no wall protection material was used. This result does not seem reasonable when compared to Rounds 17 and 19 on similar materials. Additional tests are needed on this material before an explanation can be attempted.

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TABLE 1

SUMMARY OF RESULTS

Round No.	Sample Composition: Donor Pl.	Sample Composition: Test Material	Sample Composition: Acceptor Pl.	Z Distance $X/W^{1/3}$ *	Z Distance $X/W^{1/3}$ **	Pellet Velocity ft/sec (avg)	Peak Stress psi (avg)
5, 6			2 in. AL.	0.50	0.50	102 ± 5	31,300
19		4 in. Mix No. 4	2 in. AL.	0.10	0.50	84	25,700
9	2 in. AL.	2 in. AL.	2 in. AL.	0.50	0.81	50	15,300
7, 8			2 in. AL.	0.81	0.81	48 ± 1	14,700
10, 11, 12	2 in. AL.	2 in. Sand	2 in. AL.	0.50	0.81	48 ± 2	14,700
13, 15	2 in. AL.	2 in. Mix No. 1	2 in. AL.	0.50	0.81	37 ± 1	11,300
16	2 in. AL.	2 in. Mix No. 2	2 in. AL.	0.50	0.81	31	9,500
17		4 in. Mix No. 3	2 in. AL.	0.50	0.81	39	11,900
18		4 in. Mix No. 1	2 in. AL.	0.50	0.81	65	19,900

* Z Distance measured to surface of sample nearest charge.

** Z Distance measured to surface of acceptor plate.

± Values represent maximum scatter in data.

Table 2

Mixture No. 1

Cellular Concrete (1 cu ft)

Cement	11.4 lb
Water	10.0 lb
Mearlcrete foaming time	6.8 sec
Density (plastic)	22 lb/cu ft
Density (dry)	20 lb/cu ft
Compressive Strength	70 psi
Air fraction	60 %

Mixture No. 2

Cellular Concrete (1 cu ft)

Cement	21.6 lb
Water	18.5 lb
Mearlcrete foaming time	5 sec
Density (plastic)	40 lb/cu ft
Density (dry)	30 lb/cu ft
Compressive Strength	350 psi
Air fraction	45 %

Mixture No. 3

Expanded Cement Grout (1 cu ft)

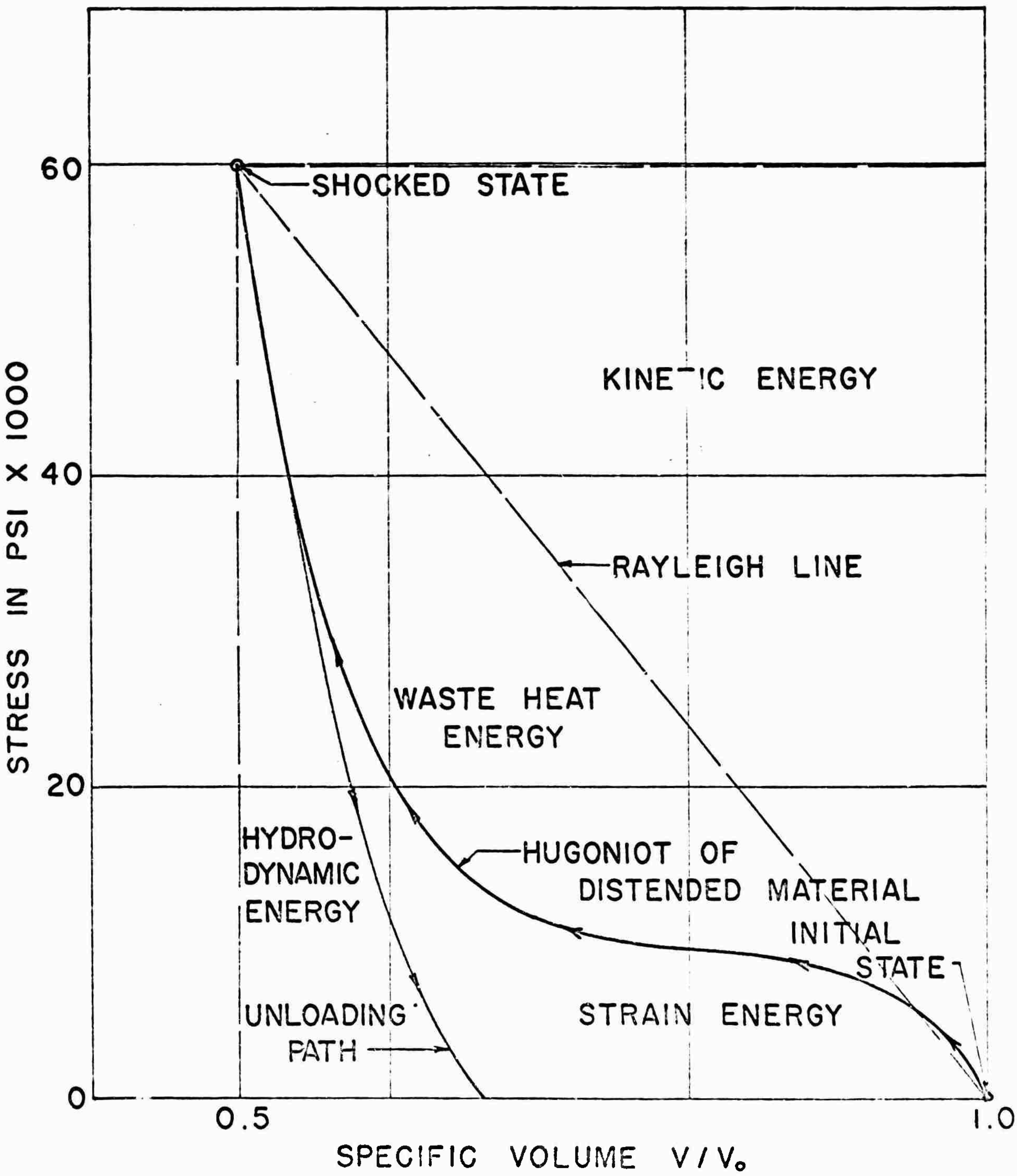
Cement	47.6 lb
Water	23.8 lb
-50 ilmenite sand	101.4 lb
Aquagel	1.27 lb
TIC	0.76 lb
Aluminum powder AP 3xD	2.03 g
Air entraining	101.4 ml
Density (plastic)	175 lb/cu ft
Density (dry)	135 lb/cu ft
Compressive Strength	3000 psi
Air Fraction	38 %

Table 2 (continued)

Mixture No. 4

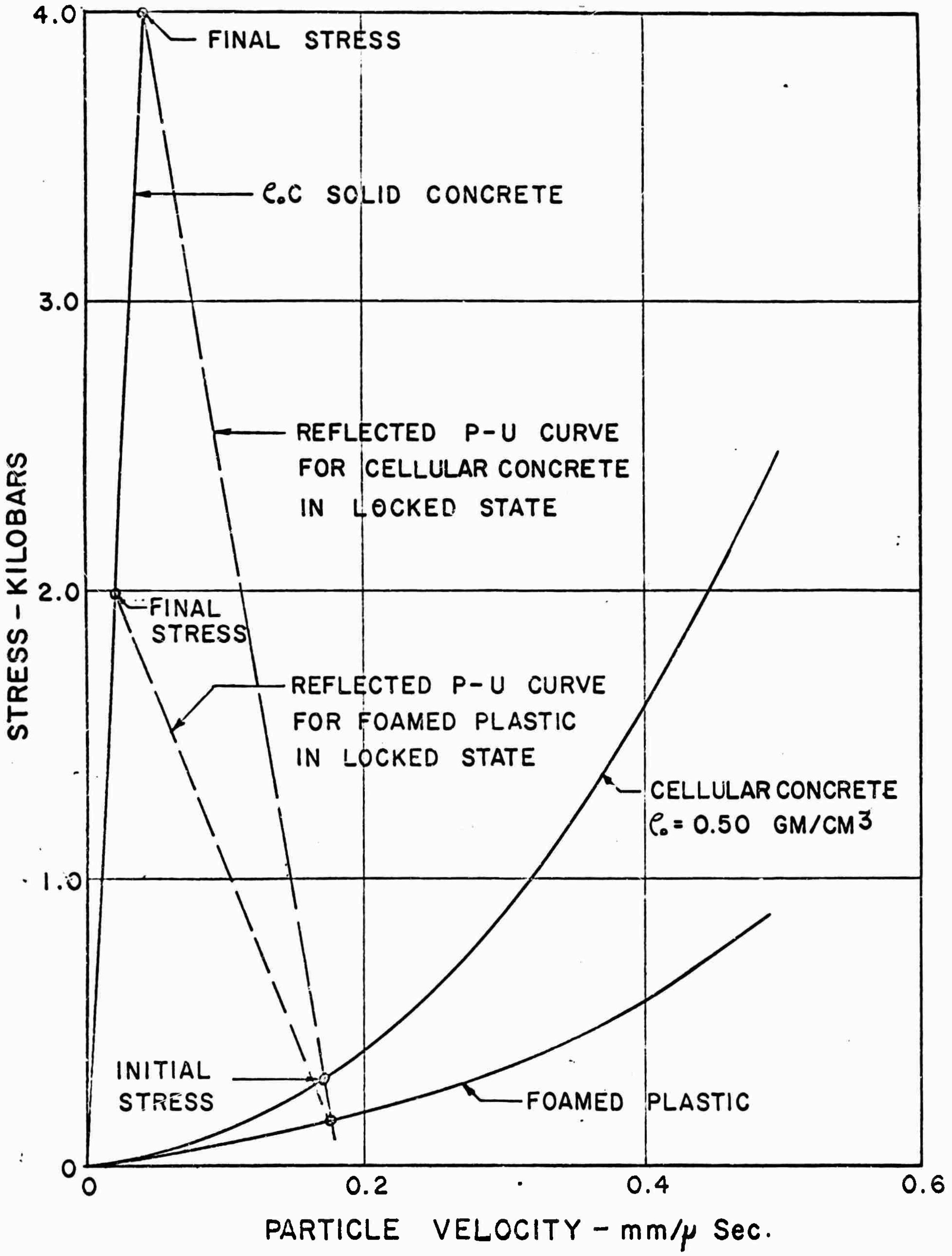
Cellular Concrete with Sand (1 cu ft)

Cement	14.7 lb
Water	11.4 lb
Mearlcrete foaming time	8.4 sec
-80 ilmenite sand	40.2 lb
Density (plastic)	67 lb/cu ft
Density (dry)	62 lb/cu ft
Compressive Strength	90 psi
Air fraction	45 %



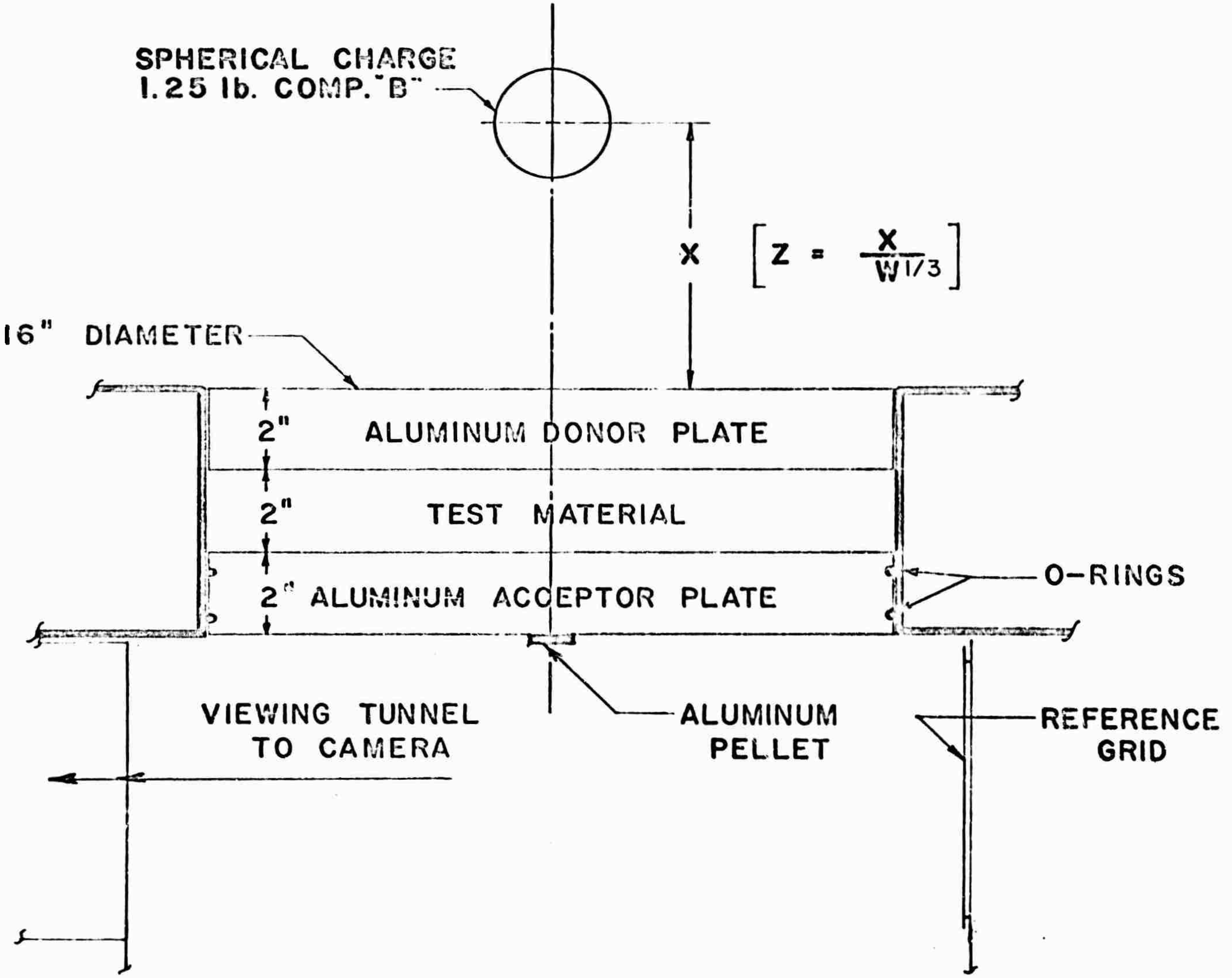
ENERGY PARTITIONING

Fig. 1



STRESS Vs. PARTICLE VELOCITY

Fig. 2



TEST CONFIGURATION

Fig. 3